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The Influence of Barbell and Body Position on Force-Time Characteristics in the Isometric Mid-Thigh Pull

This thesis is presented in partial fulfilment of the degree of
Master of Science (Sports Science)

Stuart Nathan Guppy

Principal Supervisor: Professor G. Gregory Haff

Associate Supervisor: Dr. Nikola Medic

Edith Cowan University, Australia
School of Medical and Health Sciences

2019

USE OF THESIS

The Use of Thesis statement is not included in this version of the thesis.

Abstracts

Publication 1: The Isometric Mid-Thigh Pull: A Review and Methodology – Part 1

Isometric tests are commonly used to monitor physical qualities that underpin athletic performance. As single-joint laboratory-based tests display poor relationships to the multi-joint movements found in sport, multi-joint isometric tests like the isometric mid-thigh pull (IMTP) are commonly used instead. Force-time characteristics in these multi-joint tests typically display stronger relationships to dynamic performance, particularly in the case of the isometric mid-thigh pull. As such this review focuses on the relationships between force-time characteristics in the IMTP and dynamic athletic performance.

Publication 2: The Isometric Mid-Thigh Pull: A Review & Methodology – Part 2

The isometric mid-thigh pull (IMTP) is a commonly used test for the assessment of skeletal muscle function in athletes from a wide variety of sports. Although force-generating capacity and rate of force development measured in the IMTP are related to dynamic athletic performance measures, the testing and analysis procedures used can have adverse effects on the magnitude and reliability of the force-time characteristics produced. As such, this review focuses on the correct testing and analysis methodologies to use during IMTP testing.

Publication 3: The Effect of Altering Body Posture and Barbell Position on the Within-Session Reliability and Magnitude of Force-Time Curve Characteristics in the Isometric Mid-Thigh Pull

A large degree of variation in the position used during isometric mid-thigh pull (IMTP) testing, and conflicting results of the effects of these changes, can be found in the literature. This study investigated the effect of altering body posture and barbell position on the reliability and magnitude of force-time characteristics generated during the IMTP. Seventeen strength-power athletes ($n = 11$ males, height: 177.5 ± 7.0 cm, body mass: 90 ± 14.1 kg, age: 30.6 ± 10.4 years; $n = 6$ females, height: 165.8 ± 11.4 cm; body mass: 66.4 ± 13.9 kg, age: 30.8 ± 8.7 years) with greater than 6 months of training experience in the clean (1RM: 118.5 ± 20.6 kg, 77.5 ± 10.4 kg) volunteered to undertake the experimental protocol. Subjects performed the IMTP using four combinations of hip and knee angles, and two different barbell positions. The first barbell position corresponded to the second pull of the clean, while the second rested at the mid-point between the iliac crest and the patella. Peak force (PF), time-specific force (F_{50} , F_{90} , F_{150} , F_{200} , F_{250}), peak rate of force development (pRFD), and impulse (IMP) time-bands were reliable in all four testing

positions examined. Statistically greater PF, F₅₀, F₉₀, F₁₅₀, F₂₀₀, F₂₅₀, pRFD and IMP₀₋₅₀, IMP₀₋₉₀, IMP₀₋₁₅₀, and IMP₀₋₂₀₀ were generated in a testing position corresponding to the second pull of the clean when compared to a bent over torso angle, regardless of the barbell position used. Moderate to large effect sizes favouring a testing position corresponding to the second pull were also found. Overall, when performing the IMTP, an upright torso and a barbell position that matches the second pull of the clean should be used.

Key Words: Strength Testing, Maximum Force, Rate of Force Development, Impulse, Performance Testing

Publication 4: The Effect of Altering Body Posture and Barbell Position on the Between-Session Reliability of Force-Time Curve Characteristics in the Isometric Mid-Thigh Pull

Seventeen strength and power athletes (n = 11 males, 6 females; height: 177.5 ± 7.0 cm, 165.8 ± 11.4 cm; body mass: 90.0 ± 14.1 kg, 66.4 ± 13.9 kg; age: 30.6 ± 10.4 years, 30.8 ± 8.7 years), who regularly performed weightlifting movements during their resistance training programs, were recruited to examine the effect of altering body posture and barbell position on the between-session reliability of force-time characteristics generated in the isometric mid-thigh pull (IMTP). After subjects were familiarised with the testing protocol, they undertook two testing sessions which were separated by seven days. In each session, the subjects performed three maximal IMTP trials in each of the four testing positions examined, with the testing order randomised. In each position, no significant differences were found between-sessions for all force-time characteristics (p = >0.05). Peak force (PF), time-specific force (F₅₀, F₉₀, F₁₅₀, F₂₀₀, F₂₅₀), and IMP time-bands (0-50, 0-90, 0-150, 0-200, 0-250 ms) were reliable across each of the four testing positions (ICC ≥ 0.7, CV ≤ 15%). Time to peak force, peak RFD, RFD time-bands (0-50, 0-90, 0-150, 0-200, 0-250), and peak IMP were unreliable regardless of testing position used (ICC = <0.7, CV = >15%). Overall, the use of body postures and barbell positions during the IMTP that do not correspond to the second pull of the clean have no adverse effect of the reliability of the force-time characteristics generated.

Key Words: Strength Testing, Maximum Force, Rate of Force Development, Impulse, Performance Testing

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

(1) incorporate without acknowledgement any material previously submitted for a degree or diploma in any institution of higher education;

(2) contain any material previously published or written by another person except where due reference is made in the text; or

(3) contain any defamatory material.

Stuart Nathan Guppy

Date: 19/03/2019

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Finally, my parents. You may not always understand exactly what it is that I'm doing – or why – but you've always encouraged me to pursue an education and supported me in following whatever career path that I chose, no matter what. I don't know that I can actually ever repay that. Thank you.

Academic research wasn't what I started out at university ten years ago wanting to do. In fact, it was the last thing I wanted to do. Something about not liking statistics. Instead, the plan was to finish my undergrad sports science degree and use it to go become a physiotherapist. That plan morphed into becoming an exercise physiologist, which also ended up morphing into becoming a strength and conditioning coach.

But research is exactly what I want to do from now on.

Publications related to thesis

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List of Abbreviations

avgRFD – Average Rate of Force Development

BW – Body Weight

CMJ – Countermovement Jump

CV – Coefficient of Variation

EMG – Electromyography

ES – Effect Size

F₃₀ – Force at 30 milliseconds

F₅₀ – Force at 50 milliseconds

F₉₀ – Force at 90 milliseconds

F₁₀₀ – Force at 100 milliseconds

F₁₅₀ – Force at 150 milliseconds

F₂₀₀ – Force at 200 milliseconds

F₂₅₀ – Force at 250 milliseconds

IBP – Isometric Bench Press

ICC – Intra-Class Correlation Coefficient

ILP – Isometric Leg Press

IMTP – Isometric Mid-Thigh Pull

IMP – Impulse

IMP₁₀₀ – Impulse at 100 milliseconds

IMP₂₀₀ – Impulse at 200 milliseconds

IMP₃₀₀ – Impulse at 300 milliseconds

IMP₀₋₅₀ – Impulse between 0-50 milliseconds

IMP₀₋₉₀ – Impulse between 0-90 milliseconds

IMP₀₋₁₅₀ – Impulse between 0-150 milliseconds

IMP₀₋₂₀₀ – Impulse between 0-200 milliseconds

IMP₀₋₂₅₀ – Impulse between 0-250 milliseconds

ISqT – Isometric Squat

MT – ‘Mid-Thigh’ Isometric Mid-Thigh Pull Barbell Position (i.e. the mid-point between the iliac crest and the patella)

MTP – Mid-Thigh Pull

N – Newton(s)

PF – Peak Force

PF_{kg} – Peak Force Relative to Body Weight

pIMP – Peak Impulse

PP – Peak Power

pRFD – Peak Rate of Force Development

pRFD₂₀ – Peak Rate of Force Development calculated using a 20 millisecond sampling window

RFD – Rate of Force Development

RFD₀₋₃₀ – Rate of Force Development between 0-30 milliseconds

RFD₀₋₅₀ – Rate of Force Development between 0-50 milliseconds

RFD₀₋₉₀ – Rate of Force Development between 0-90 milliseconds

RFD₀₋₁₅₀ – Rate of Force Development between 0-150 milliseconds

RFD₀₋₂₀₀ – Rate of Force Development between 0-200 milliseconds

RFD₀₋₂₅₀ – Rate of Force Development between 0-250 milliseconds

RM – Repetition Maximum

SD – Standard Deviation

SJ – Squat Jump

SWC – Smallest Worthwhile Change

TE – Typical Error

TRAD – ‘Traditional’ Isometric Mid-Thigh Pull Barbell Position (i.e. the second pull)

TtPF – Time to Peak Force

VJ – Vertical Jump

1RM – One Repetition Maximum

Chapter 1 – Introduction

1.1 Background to the research

The improvement of key physical abilities that underpin successful sports performance, such as sprinting, jumping, and change of direction, is a primary goal of both strength and conditioning professionals and athletes (55). To successfully optimise the performance of these physical abilities, and improve both selection status (8, 49, 126) and playing level (2, 5, 6), athletes require a minimum threshold of muscular strength and power (44, 61, 87). In addition to influencing both selection status and playing level, an athlete's maximal strength levels affects the performance of sports skills (112, 113). For example, Speranza et al. (112) reported that levels of both muscular strength and muscular power are related to the tackling ability of semi-professional rugby league athletes. Further research by Speranza et al. (113) demonstrated that increases in maximum strength and power improve tackling ability, a key factor of success in collision sports such as rugby league, rugby union, and American football (47, 104).

An athlete's maximal strength level also influences key markers of athletic performance such as sprinting, particularly over the short distances commonly found in field-based team sports. McBride et al. (86) demonstrated that athletes with a one repetition maximum (1RM) back squat relative to body weight (BW) of $>2.1 \times \text{BW}$ are significantly faster over distances of 10 and 40 yards than their weaker peers (relative 1RM squat = $<1.9 \times \text{BW}$). Similarly, Comfort et al. (30) demonstrated that increasing rugby league players' relative 1RM back squat strength from $1.78 \times \text{BW}$ to $2.05 \times \text{BW}$ results in significant decreases in five (7.6%), ten (7.3%), and twenty (5.9%) meter sprint time. As net ground reaction force is a key determinant of sprint speed (73), it is plausible that high levels of lower body maximum strength are required to produce the requisite forces necessary for successful sprint performance. As such, athletes commonly undertake intensive resistance training and monitoring programs to ensure the required levels of maximal strength and power are developed. Typically, these monitoring programs include a battery of both dynamic and isometric testing modalities, with each modality providing feedback to strength and conditioning professionals about the athletes' bio-motor and physical abilities (88). This feedback allows for the alteration of training interventions to ensure that the desired adaptation(s) to the prescribed training stimulus occurs (89, 95).

Dynamic tests of maximum strength and power are commonly utilized in applied environments due to their strong relationships with the dynamic movements found in

sport and the wide availability of required equipment (9, 13, 14, 88, 89). Maximum strength is typically measured through the performance of a repetition maximum (RM) in movements such as the back squat (86), deadlift (65) or bench press (11), while muscular power is often assessed through the performance of explosive movements such as loaded and unloaded jumps (13, 116) or bench throws (7, 134). While these dynamic tests are extremely reliable (32) and provide valuable information about the physical condition of the athlete, there are several potential limitations that may preclude their use as assessment tools in a regular athlete monitoring program. First, due to the maximal loads used during RM strength testing, some practitioners have suggested the performance of dynamic maximal strength testing presents an excessively high risk of injury to non-strength sport athletes (76), although this view remains as yet unsupported by the current body of scientific literature. Furthermore, the maximal loads inherent in RM strength testing results in high levels of accumulated fatigue (24, 72), adversely affecting subsequent technical and tactical training sessions and thereby is potentially detrimental to sport performance. Finally, the use of a single dynamic movement as the sole measure of strength or power may not be sensitive enough to determine significant changes from baseline levels, therefore masking potential changes in skeletal muscle function (26). Both Martin-Hernandez et al. (85) and Mitchell et al. (97) reported significantly greater dynamic strength increases in individuals performing high load resistance exercise compared to low load resistance exercise despite no significant differences between groups being reported in measures of isometric strength, rate of force development (RFD) or maximal instantaneous power output during isokinetic dynamometry. Therefore, it is possible that within a comprehensive athlete monitoring program, both dynamic and isometric measures of skeletal muscle function are required to more accurately assess the physical capacity of the athlete.

Unlike many traditional dynamic testing modalities, isometric tests allow for the assessment of skeletal muscle function through the evaluation of an isometric force-time curve. While a dynamic test of maximum strength such as the 1RM back squat allows for the reliable assessment of global lower body strength and is easily performed in the applied environment, isometric testing modalities allow for the assessment of multiple bio-motor abilities, such as maximal force, RFD, and impulse (IMP), within a single trial. Furthermore, isometric tests are traditionally considered to be biomechanically simple in design and the use of these testing modalities removes, to a large extent, the effect of training-induced skill acquisition, which may be a confounding variable when using a

dynamic movement such as the squat as both a training and assessment tool (26). This therefore allows for the assessment of skeletal muscle function in large groups of athletes, common in the team sport environment, in a time efficient manner.

Traditionally, isometric testing has been performed in laboratory environments, using single-joint movements such as the knee extension performed in an isokinetic dynamometer (14, 109, 110). While these testing methodologies provide accurate and reliable measures of skeletal muscle function, the force-time characteristics displayed in these movements are typically weakly related to performance in the explosive dynamic multi-joint movements commonly found in the sporting environment (98, 99, 130). As such, in applied sport settings, the use of multi-joint isometric tests such as the isometric squat (ISqT) and isometric mid-thigh pull (IMTP) have become increasingly prevalent due to the strong relationships between the force-time characteristics displayed in these tests and multi-joint movements found in specific sports (16, 21, 62, 137). However, while these relationships may be strong, they also appear to be joint-angle specific (16, 21) and therefore these tests may not truly assess skeletal muscle function. For example, while the peak force (PF) generated in the ISqT is strongly related to performance in the 1RM full and partial back squat, the magnitude of this relationship is dependent on the knee angle used during both isometric and dynamic testing (16). Bazyler et al. (16) reported the relationship between PF at a 90° knee angle and 1RM back squat performance is stronger ($r = 0.864$, $r^2 = 0.746$) than the relationship between PF at a 120° knee angle and 1RM squat performance ($r = 0.597$, $r^2 = 0.356$). Similarly, PF at 120° knee angle demonstrates a stronger relationship, although only slightly, to partial back squat (120°) 1RM ($r = 0.789$, $r^2 = 0.623$) than PF at a 90° knee angle ($r = 0.705$, $r^2 = 0.497$) (16).

The isometric leg press (ILP), while reliable in the measurement of isometric force and RFD characteristics (84, 139, 140), demonstrates similar joint-angle specificity in the relationships between the force-time characteristics displayed and dynamic performance. Marcora & Miller (84) reported that while moderate to strong relationships ($r = 0.50$ - 0.71) exist between PF and RFD at a knee angle of 120° and both squat- and counter-movement jump height, these relationships do not exist when the ILP is performed at a knee angle of 90°. As such, while the relationships between force-time characteristics generated in the ISqT and ILP and dynamic performance are stronger than the relationships between force-time characteristics generated in single-joint movements and dynamic performance, they are joint-angle specific. Due to this limitation, it is possible

that attaining an accurate and sufficiently clear assessment of skeletal muscle function may not be possible when using these isometric testing modalities. However, based on the current literature, the IMTP may provide a clearer assessment of an athlete's skeletal muscle function than the previously described multi-joint isometric tests.

First introduced into the scientific literature in 1997, the IMTP was originally designed to facilitate the monitoring of physical qualities deemed important to weightlifting performance (57). Therefore, the body posture and barbell position used were selected to closely match those found during the initiation of the second pull during the clean (53, 57). It has previously been established that this position results in the highest force output and barbell velocities during the clean (41, 42, 50, 58). Briefly, performance of the IMTP entails the placement of the athlete in a position mimicking the second pull of the clean, after which they pull on an immovable barbell with maximal effort for approximately five seconds (57). A force platform positioned below the athlete's feet allows for the recording of vertical ground reaction force and therefore the production of a force-time curve, from which force-generating capacity, RFD, and IMP can be calculated (56, 57).

Due to the IMTP testing position being mechanically similar to the second pull position during both the clean and snatch, it is not surprising that force-time variables such as PF are closely related to performance in the clean and jerk ($r = 0.84$, $r^2 = 0.70$), snatch ($r = 0.83$, $r^2 = 0.69$), and summated total ($r = 0.84$, $r^2 = 0.70$) (17). Furthermore, derivatives of the weightlifting movements such as the power clean ($r = 0.57$ - 0.67) (39) and power snatch ($r = 0.94$ - 0.98) (117) display similar strong relationships to PF generated during the IMTP. In addition to the relationships found between PF in the IMTP and weightlifting movements, similar relationships have been found between PF in the IMTP and 1RM squat (90, 91), deadlift (133), and bench press (91) strength. Taken collectively, this suggests that the IMTP is a viable alternative that enables monitoring of changes in global maximal strength without requiring athletes to frequently perform maximal tests in dynamic movements.

Force-time characteristics in the IMTP also demonstrate weak to moderately strong relationships to common markers of dynamic athletic performance such as sprinting, jumping, and change of direction (57, 80, 119, 128). West et al. (128) reported that that relative PF ($r = -0.37$) and both absolute ($r = -0.54$) and relative force ($r = -0.68$) at 100 ms (F_{100}) demonstrate a significant negative relationship with 10 metre sprint time. Thomas

et al. (119) report similar negative relationships between PF and short sprint performance over both five ($r = -0.57$) and twenty metre ($r = -0.69$) distances. These relationships are likely due to the short ground contact times (<100 ms) commonly found during sprinting movements (96) and the relationship between greater ground reaction forces and faster sprinting speed (129). Thomas et al. (119) also reported that PF in the IMTP has a moderately strong negative relationship ($r = -0.57$) with 5-0-5 change of direction performance, which aligns with the results of Spiteri et al. (114) who demonstrated that stronger athletes have superior deceleration and re-acceleration ability during a change of direction task.

Similar to force characteristics, strong negative relationships have been found between IMP characteristics generated in the IMTP and both short sprint and change of direction performance. The volume of evidence of these relationships is however limited within the contemporary scientific literature. Thomas et al. (119) reported that IMP at 100 (IMP_{100}) and 300 ms (IMP_{300}) displayed strong negative relationships to sprint performance over distances of five ($r = -0.71$ - -0.74) and twenty metres ($r = -0.75$ - -0.78) in field sport athletes. Similar, though slightly weaker, relationships were found between IMP_{100} ($r = -0.58$) and IMP_{300} ($r = -0.62$) to performance in the 5-0-5 change of direction test (119). Furthermore, an extremely limited number of investigations exist within the literature examining the relationship between IMP in the IMTP and jumping performance. Thomas et al. (121) reported that while absolute peak IMP (pIMP), IMP_{100} , and IMP_{300} are significantly related ($r = 0.49$ - 0.64) to PF and peak power (PP) output in both the countermovement and squat jump, no relationships exist between absolute or relative measures of these characteristics and jump height. Furthermore, relative pIMP, IMP_{100} and IMP_{300} displayed no relationship to both countermovement and squat jump PF and PP. This is somewhat surprising considering Kirby et al. (78) reported that relative net vertical IMP during jumping movements was very strongly related to, and ultimately determines, jump height in both static ($r = 0.93$) and countermovement ($r = 0.92$) jumps.

Importantly, while force-time characteristics in the IMTP display moderate to strong relationships to performance in dynamic tasks commonly found in many sports, the magnitude and reliability of those force-time characteristics are reliant on the testing protocol and subsequent analysis procedures used (22, 38, 83). Originally, Haff et al. (56) utilized a IMTP testing position that matched the barbell position and body posture of the second pull of the clean. This position has been extensively used throughout the literature

(4, 17, 53, 54, 71, 101, 118), however there has been an increasing prevalence of deviation in the body posture and barbell position used away from a position corresponding to the second pull of the clean, as use of the IMTP as a monitoring tool has increased in frequency. McGuigan et al. (90) reported the use of a barbell position resting just above the knee in conjunction with a knee angle of 130° . Comfort et al. (31) utilised a barbell position at the mid-point between the middle of the patella and the iliac crest, which Wang et al. (127) subsequently used during testing of collegiate rugby union athletes. Similar variation in the body posture used during the IMTP has occurred in the literature with average hip- and knee-angles of 124° - 175° and 130° - 145° reported (17, 20, 23, 53, 54, 56, 57, 101).

Although alterations in the body posture and barbell position used during the IMTP typically result in reliable measures of force characteristics (20, 31), there is conflicting results in the literature regarding whether the magnitude of force characteristics generated is affected by changes in both body posture and barbell position. Comfort et al. (31) reported that provided the barbell was maintained at a position at the mid-point between the patella and the iliac crest, nine different combinations of hip- and knee-angles resulted in no significant differences in PF output. Beckham et al. (19) however demonstrated in powerlifters that an IMTP testing position comprising an upright torso and barbell position that approximates the second pull of the clean results in significantly greater PF values than a barbell position of above the knee and a resultant “bent-over” torso position. Similarly, Beckham et al. (20) reported that both PF and time specific force (50, 90, 200, 250 ms) were greater in a barbell position matching the second pull and with hip- and knee-angles of 145° and 125° respectively when compared to the barbell position used by Comfort et al. (31) and hip- and knee-angles of 125° . Beckham et al. (20) also reported that several participants were either unable to attain the “bent-over” torso position with a lower barbell position or changed body posture substantially upon trial initiation, in a manner similar to the repositioning found during the transition from the first pull to the second pull during the clean (58). Furthermore, Dos’Santos et al. (37) reported that an “upright” torso angle of 145° results in significantly greater force output and RFD variables than a “reclined” torso angle of 175° .

As such, while there is an increasing body of evidence that shows force output is substantially affected by alterations in IMTP testing position, there is however only limited evidence examining the effect of altering IMTP testing position on the magnitude

and reliability of RFD and IMP characteristics. Like PF, Comfort et al. (31) reported that alterations in body posture do not result in significant differences between the maximum RFD (pRFD) values calculated using a 1.67 ms sampling window in each body posture, provided the barbell was maintained at the mid-point between the patella and the iliac crest. Beckham et al. (19) and Beckham et al. (20) however did not report RFD or IMP characteristics while comparing the effect of changes in both body posture and barbell position on force-time characteristics. It is plausible that given force-generating capability is a key underpinning determinant of RFD and IMP (43, 83), changes in body posture and barbell position will affect the magnitude of both force-time characteristics.

Similarly, there is very limited evidence of the effect of changes in IMTP testing position on the reliability of RFD and IMP characteristics, as only changes in body posture have been examined. For example, while Comfort et al. (31) reported that pRFD calculated using a 1.67 ms sampling window and IMP at 100, 200, and 300 ms were reliable regardless of body posture providing the barbell was maintained at the mid-point between the patella and the iliac crest, Beckham et al. (19) and Beckham et al. (20) did not report these characteristics at all. Both Haff et al. (56) and Brady et al. (23) however demonstrated that the sampling window used by Comfort et al. (31) was unreliable for the calculation of pRFD in the IMTP when performed in a position matching the second pull of the clean, while Brady et al. (23) also reported that only IMP in the 0-300 ms time band was reliable. Furthermore, Beckham et al. (19), Beckham et al. (20), and Comfort et al. (31) did not examine RFD time-bands, which both Haff et al. (56) and Brady et al. (23) have demonstrated to be more reliable than pRFD for the assessment of skeletal muscle function. As such, the results of the effect of altering IMTP testing position on force, RFD, and IMP characteristics seem to be conflicting within the current literature, and is therefore a topic that warrants further research.

1.2 Purpose of research

The purpose of this thesis was to determine what effect alterations in body posture have upon the reliability and magnitude of force-time characteristics in the isometric mid-thigh pull, particularly rate of force development and impulse. This purpose was addressed through two studies.

Study one was designed to investigate the effect of changes in body posture and barbell position on the between-session reliability of force-time characteristics produced in the

IMTP. In study two, the aim was to determine whether changes in body posture and barbell position affected the magnitude of the force-time characteristics produced in the IMTP

1.3 Significance of research

Given the IMTP is an increasingly popular and practical tool for the assessment of skeletal muscle function in athletic populations, inconsistencies in the methodologies used within the current literature prevent a definitive guide on which testing position should be adopted during the performance of the IMTP being established. Furthermore, to the best of the author's knowledge, no study within the current literature has reported the effect of altering body posture and barbell position on time-specific RFD and IMP characteristics. Given the highest barbell velocities and force outputs have been reported during dynamic performance of the second pull of the clean, it is plausible that failing to adopt a corresponding position during performance of the IMTP will substantially affect the RFD and IMP characteristics generated.

Therefore, the primary purpose of this thesis was to provide a clearer understanding of the effect of altering body posture and barbell position on all force-time characteristics generate during the performance of the IMTP. From the novel findings of this theses it is therefore possible to provide strength and conditioning professionals guidelines for the most appropriate testing position that allows for the accurate assessment of skeletal muscle function. Moreover, the improved assessment accuracy facilitated by these guidelines allows for superior design of subsequent training interventions, thereby benefiting the athletes through improvements in sports performance.

1.4 Research Questions

1. What effect does the altering of the IMTP testing position used from one corresponding to the second pull of the clean have upon the magnitude of force, rate of force development, and impulse characteristics generated?
2. Does using an IMTP testing position other than one corresponding to the second pull of the clean affect the reliability of force-time characteristics generated between sessions?

1.5 Hypotheses

1. A body posture and barbell position in the IMTP that matches the second pull of the clean will result in significantly greater force, rate of force development and impulse characteristics than altered body postures and barbell position.
2. A body posture and barbell position in the IMTP that corresponds to the second pull of the will result in force, rate of force development, and impulse characteristics that are reliable between sessions, while alterations in body posture and barbell position will reduce reliability.

Chapter 2 - Publication 1

This chapter is not available in this version of the thesis

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Guppy, S.N., Brady CJ, Comfort P, and Haff GG. (2018). The Isometric Mid-Thigh Pull: A Review & Methodology - Part 1. *Professional Strength & Conditioning*, 51: 13-19. Article is available <https://www.uksca.org.uk/uksca-iq-article/performance-assessments/1835/the-isometric-mid-thigh-pull-a-review-and-methodology-part-1>

Chapter 3 - Publication 2

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Chapter 5 - Publication 4

The Effect of Altering Body Posture and Barbell Position on the Between-Session Reliability of Force-Time Characteristics in the Isometric Mid-Thigh Pull

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5.1 Introduction

Isometric tests, such as the isometric mid-thigh pull (IMTP), enable efficient assessment of skeletal muscle function in athletic populations. As isometric tests produce a force-time curve, it is possible to assess multiple physical characteristics underpinning sports performance, such as force generating capacity, rate of force development (RFD) and impulse (IMP) within a single trial (83, 95). Furthermore, when performed in conjunction with traditional dynamic measures of strength (one repetition maximum squat, deadlift and bench press) (32, 65) or power (jumping and throwing movements) (89), the use of isometric tests may provide a clearer assessment of changes induced by training interventions than relying on a single dynamic measure (26). While single-joint laboratory-based isometric tests, such as knee extension or plantar-flexion, typically display poor relationships to dynamic multi-joint movements commonly found in sport (1, 14, 98), multi-joint isometric tests such as the IMTP have been shown to display strong relationships to dynamic athletic performance (118, 119, 121) and are therefore commonly used in applied sport settings.

Originally designed, in part, as a monitoring tool for physical characteristics underpinning successful performance in weightlifting, the testing position used during the performance of the IMTP closely corresponds to the second pull position found in the clean (53, 57). Importantly, during dynamic performance of the weightlifting movements, this position results in the highest barbell velocity and force output (41, 42, 58). Due to this mechanical similarity between the isometric and dynamic positions, peak force (PF) in the IMTP is highly correlated with performance in both the clean & jerk ($r = 0.84$) and snatch ($r = 0.83$), along with competition total ($r = 0.84$) (17). Furthermore, PF is correlated with performance in derivatives of the weightlifting movements such as the power clean ($r = 0.57$ – 0.67) (39) and power snatch ($r = 0.94$ – 0.98) (117). In addition to its use in weightlifting as a monitoring tool, the IMTP has been used in several other sports (25, 71, 101), with both force and RFD characteristics being related to performance in common sporting movements such as sprinting (119), jumping (121), throwing (117) and change of direction (119), along with being used as a fatigue monitoring tool in tennis (51).

Because of the increasingly common use of the IMTP as an assessment tool within comprehensive athlete monitoring programs it is important that the force-time characteristics used to assess the athletes' skeletal muscle function are reliable and

therefore provide accurate information about the effect of both competition and training upon an athlete's physical condition (67). Previous research by Haff et al. (56) has demonstrated that PF, time-specific force and RFD time-bands are reliable in the IMTP when using a body posture and barbell position that matches the position originally described by Haff et al. (57). Peak RFD (pRFD), however, was unreliable unless calculated using a 20 ms sampling window (56). Conversely, Brady et al. (23), using the same testing position as Haff et al. (56), reported that both RFD time-bands up to and including 0–150 ms and pRFD calculated in all sampling windows (2, 5, 19, 20, 30, 50 ms) are unreliable. Therefore, based on the current literature it remains unclear whether RFD time-bands are reliable methods for assessing skeletal muscle function in the IMTP.

Furthermore, as a result of the increasingly common use of the IMTP as an assessment tool, the body postures and barbell positions reported in the scientific literature have deviated substantially from the positions originally described by Haff et al. (57). McGuigan et al. (90) reported the use of a barbell position that varied based on the athlete attaining a standardised knee angle of 130°, while Comfort et al. (31) reported the use of a barbell position that was the mid-point between the middle of the patella and the iliac crest, a position subsequently used by Wang et al. (127). Comfort et al. (31) demonstrated that the between-session reliability of measurements of PF, maximum RFD (mRFD) using a 1.67 ms sampling window and impulse at 100 (IMP₁₀₀), 200 (IMP₂₀₀) and 300 (IMP₃₀₀) ms is unaffected by changes in body posture provided the barbell position is maintained at the mid-point between the middle of the patella and the iliac crest. Subsequently however, Thomas et al. (120) reported small but significant differences in the IMP₁₀₀, IMP₂₀₀ and IMP₃₀₀ generated between sessions, conflicting with the results of Comfort et al. (31).

While Comfort et al. (31) reported that pRFD calculated using a 1.67 ms sampling window is reliable both within- and between-session, pRFD calculated using both a 1 and 2 ms sampling window has been demonstrated as unreliable within-session by both Haff et al. (56) and Brady et al. (23). This therefore makes comparing the between-session reliability of pRFD calculated using a 1.67 ms sampling window difficult, as there is a distinct possibility that the pRFD values calculated in the two discrete testing sessions are unreliable. Furthermore, Beckham et al. (20) reported that during trials utilising the barbell position and body posture reported by Comfort et al. (31), the

subjects displayed considerable changes in body posture upon force application. It is plausible that this change in position during the test may adversely affect the reliability of the force-time characteristics produced in those testing positions, particularly time-specific force, RFD and impulse (IMP) which are sensitive to joint angle changes during trials (83). RFD time-bands, which are potentially more reliable than pRFD measures (23, 56), were not reported by Beckham et al. (20) or Comfort et al. (31) and therefore the effect of altering body posture on the reliability of these RFD variables remains unknown to date.

Therefore, the main purpose of this study was to determine the effect of altering the body posture and barbell position used during the performance of the IMTP on the between-session reliability of force-time characteristics produced during maximal trials. We hypothesised that an IMTP testing position that matched the body posture and barbell position found at the initiation of the second pull of the clean would result in reliable measures of force, RFD and impulse, while altering this position would result in unreliable measures.

5.2 Materials and Methods

5.2.1 Participants

Seventeen strength-power athletes ($n = 11$ males, 6 females; height: 177.5 ± 7.0 cm, 165.8 ± 11.4 cm; body mass: 90.0 ± 14.1 kg, 66.4 ± 13.9 kg; age: 30.6 ± 10.4 years, 30.8 ± 8.7 years) with more than 6 months of training experience in the clean (1RM: 118.5 ± 20.6 kg, 77.5 ± 10.4 kg) volunteered to undertake the experimental protocol, however one participant substantially altered their body position during all trials and therefore was excluded on the basis that data collected did not accurately reflect force-time characteristics in each of the four positions. Participants were instructed to perform no training the day prior to testing. All participants read and signed informed consent forms prior to participation in the study as required by the Edith Cowan University Human Research Ethics Committee (Project 16377).

5.2.2 Experimental Approach to the Problem

A randomised and counter-balanced testing protocol was utilised to evaluate the effects of altering barbell position and hip- and knee-angles upon the reliability of force-time characteristics produced in the IMTP. Participants undertook three testing sessions, with the first serving to familiarise them with the experimental protocol and for the

collection of anthropometric data (height, body mass, right femur length), barbell height and grip width. The subsequent two testing sessions were then conducted 7 days apart, with participants performing three maximal effort IMTPs in each of the four positions presented in Table 5.1 during each session.

5.2.3 Warm-Up Procedures

Prior to commencing maximal IMTP testing, participants performed a dynamic warm up that included performance of dynamic mid-thigh pulls (1 set of 3 repetitions) at 40%, 60% and 80% of their 1RM clean (31). Once the dynamic warm-up was completed, the participants performed two submaximal IMTP's at 50% and 75% of perceived maximal effort.

5.2.4 Isometric Mid-Thigh Pull Testing

Once the warm-up had been completed, participants were placed in the first testing position, with the order of position used randomised. Hip- and knee-angles were confirmed using hand-held goniometry. Two different barbell positions were used, with the first, termed 'TRAD,' corresponding to the second pull position during the clean as described by Haff et al. (56). The second, termed 'MT,' corresponded to the mid-point between the iliac crest and the middle of the patella as outlined by Comfort et al. (31). During IMTP trials using the 'MT' barbell position, the immovable barbell was required to cover a tape line placed on the participant's right leg at the mid-point between the iliac crest and patella. Two different combinations of hip- and knee-angles were used for each barbell position based upon body postures reported within the literature (20, 31, 57). Both an upright (TRAD 1 & MT 2) and inclined (TRAD 2 & MT 1) torso position were assessed in each barbell position. The specific combinations of hip- and knee-angles found in each of the four testing positions assessed are outlined in Table 5.1.

TABLE 5.1 BARBELL POSITION AND HIP- AND KNEE-ANGLES FOR EACH OF THE FOUR EXPERIMENTAL POSITIONS

Condition	Barbell Position	Knee Angle	Hip Angle
TRAD 1	Traditional	~145°	~145°
TRAD 2	Traditional	~145°	120°
MT 1	Mid-Thigh	120°	125°
MT 2	Mid-Thigh	120°	145°

Participants were secured to the immovable barbell using weightlifting straps to prevent their hands from slipping during maximal trials (17). All trials were performed in a custom-designed power rack (Fitness Technology, Adelaide, Australia), which enables the barbell to be positioned at any height through a combination of pins and hydraulic jacks, whilst standing on a force-plate (BP21001200, AMTI, Newton, MA, USA), sampling at 1000 Hz. Vertical ground reaction forces were collected via a BNC-2090 interface box with an analogue-to-digital card (NI-6014, National Instruments, Austin, TX, USA). Once positioned, participants performed 3 maximal IMTPs in each of the four positions. Each trial was separated by 1 min of rest and each position was separated by 2 min of rest. Prior to testing, participants were instructed to “*pull as hard and as fast as possible*” and strong verbal encouragement was provided to ensure this occurred (59). Trials began after a countdown “3, 2, 1, Pull” with participants applying maximum effort for 5 s or until the force trace had visually declined, whichever occurred first. If there was a difference in recorded PF of greater than 250 N between trials (80) or a countermovement was visually obvious during real-time observation of the stable force trace established immediately prior to trial initiation, that trial was excluded and an additional trial was performed (25, 29).

5.2.5 Isometric Force-Time Curve Analysis

All collected force-time curves were analysed using custom LabVIEW software (Version 14.0, National Instruments). The onset of force application for each trial was determined visually, with this method chosen over automated methods as it has been performed previously in the literature relating to the IMTP (20) and is suggested as the gold standard method for force onset detection in isometric trials (123, 124). After analysis, the average value of each force-time characteristic generated across the three trials was calculated for each position in a custom Excel spreadsheet (Microsoft, Redmond, WA, USA). The maximum force generated during each IMTP trial was reported as the PF. Additionally, force at 50, 90, 150, 200 and 250 milliseconds (ms) from the initiation of the pull was calculated for each trial. pRFD using a 20 ms sampling window, RFD time-bands (0–50 ms, 0–90 ms, 0–150 ms, 0–250 ms), peak IMP (pIMP) and IMP time-bands (0–50 ms, 0–90 ms, 0–150 ms, 0–200 ms, 0–250 ms) were also calculated utilising the methods outlined by Haff et al. (56) and Enoka (43) respectively. Body weight was included in the calculation of all force-time variables, allowing comparison to force-time characteristics previously presented within the literature (17).

5.2.6 Statistical Analysis

Paired comparisons ($p < 0.05$) were performed in conjunction with a Holm's Sequential Bonferroni correction for controlling Type I error (66) to determine if significant differences existed between force-time variables produced during each testing session. Reliability of each force-time variable was assessed by determining the intraclass correlation coefficient (ICC), coefficient of variation (CV) and 95% confidence interval (CI) of log-transformed data in an Excel spreadsheet (69). Reliability was deemed acceptable at an $ICC \geq 0.7$ and a $CV \leq 15\%$ (3). Both typical error (TE) (69) and smallest worthwhile change (SWC) were calculated for all reliable force-time characteristics in each of the four testing positions. The SWC was determined by multiplying the between-subject SD by 0.2 ($SWC_{0.2}$) (68), which is a small effect, or 0.5 ($SWC_{0.5}$) (28), which is a moderate effect.

5.3 Results

No significant differences were found between sessions for any force-time variable produced in each of the four positions. Figure 5.1 shows the reliability of all force measures. PF and all time-specific force characteristics were deemed reliable in each position. Time to peak force (TtPF) did not meet either criteria in any position. The reliability statistics for both RFD and IMP variables are shown in Figure 5.2 and Figure 5.3 respectively. pRFD and all RFD time-bands were unreliable in each of the four conditions. Similarly, peak impulse (pIMP) was unreliable across all four conditions. All IMP time-bands however, were reliable regardless of testing position used. Descriptive statistics for force-time characteristics that met the required reliability criteria are shown in Table 5.2 for TRAD 1, Table 5.3 for TRAD 2, Table 5.4 for MT 1 and Table 5.5 for MT 2.

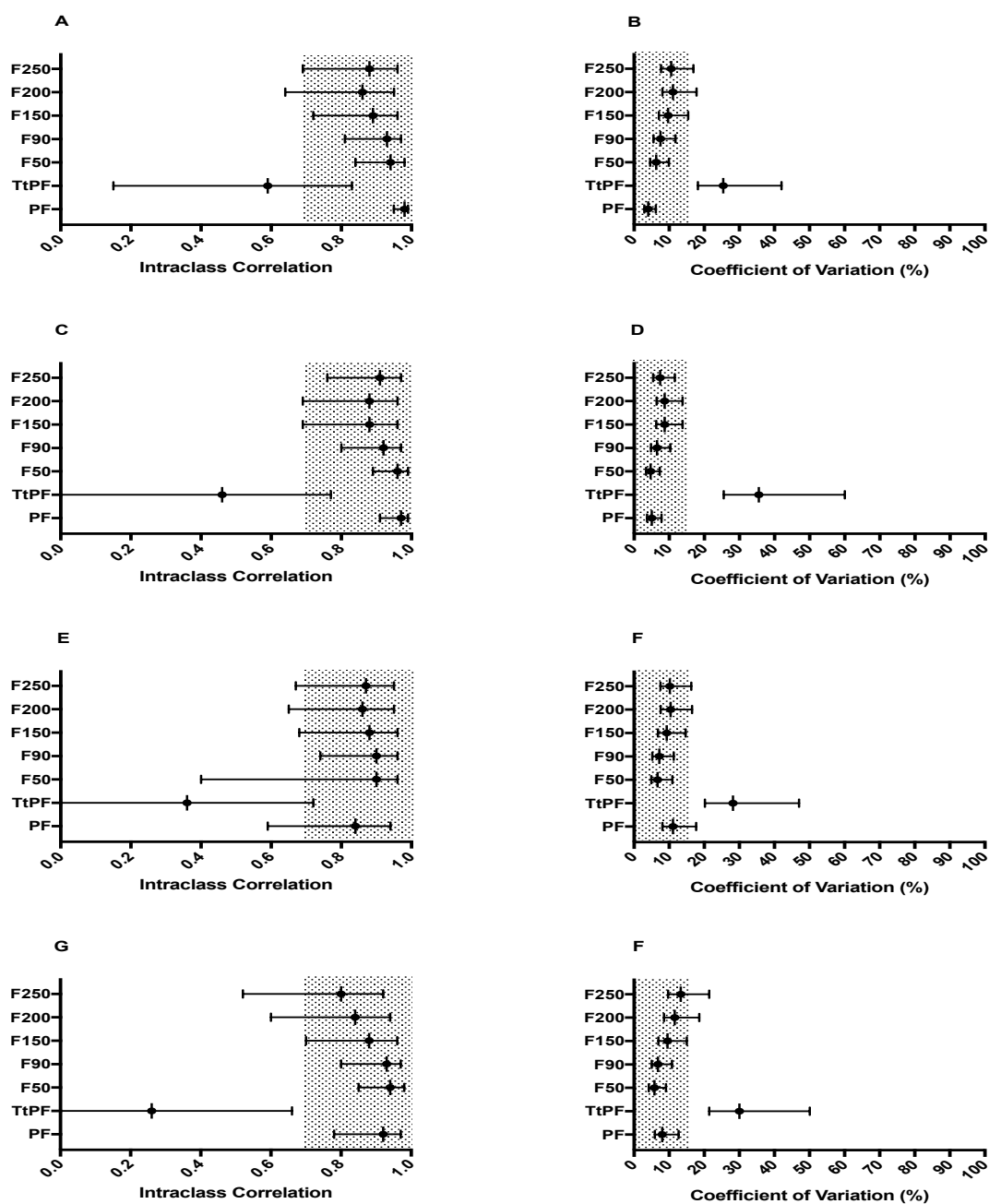


Figure 5.1 Between-Session Reliability Statistics for Force Characteristics for Each of the Four Testing Positions

Note: Grey shaded areas represented acceptable reliability ($ICC \geq 0.7$, $CV \leq 15\%$), error bars indicate 95% confidence limits. (A) ICC force characteristics in TRAD 1, (B) CV (%), (C) ICC force characteristics in TRAD 2, (D) CV (%), (E) ICC force characteristics in MT 1, (F) CV (%), (G) ICC force characteristics in MT 2, (H) CV (%). PF, peak force; TtPF, time to peak force; F50, force at 50 ms; F90, force at 90 ms; F150, force at 150 ms; F200, force at 200 ms; F250, force at 250 ms.

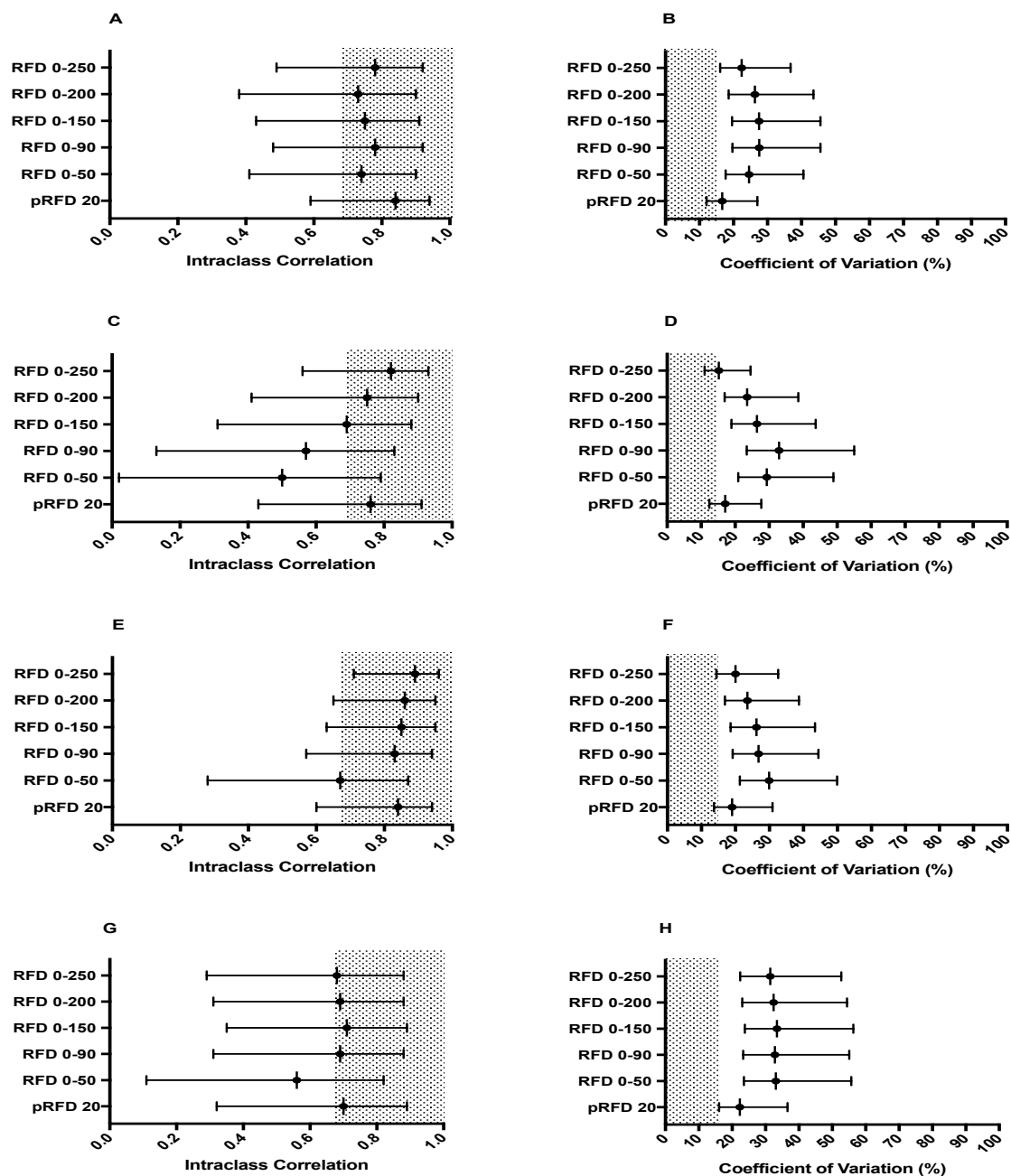


Figure 5.2 Between-Session Reliability Statistics for RFD Characteristics in Each of the Four Testing Positions

Note: Grey shaded areas represented acceptable reliability ($ICC \geq 0.7$, $CV \leq 15\%$), error bars indicate 95% confidence limits. (A) ICC RFD characteristics in TRAD 1, (B) CV (%), (C) ICC RFD characteristics in TRAD 2, (D) CV (%), (E) ICC RFD characteristics in MT 1, (F) CV (%), (G) ICC RFD characteristics in MT 2, (H) CV (%). pRFD indicates peak RFD; pRFD 20, pRFD 20 ms sampling window; RFD 0–50, RFD 0–50 ms sampling window; RFD 0–90, RFD 0–90 ms sampling window; RFD 0–150, RFD 0–150 ms sampling window; RFD 0–200, RFD 0–200 ms sampling window; RFD 0–250, RFD 0–250 ms sampling window.

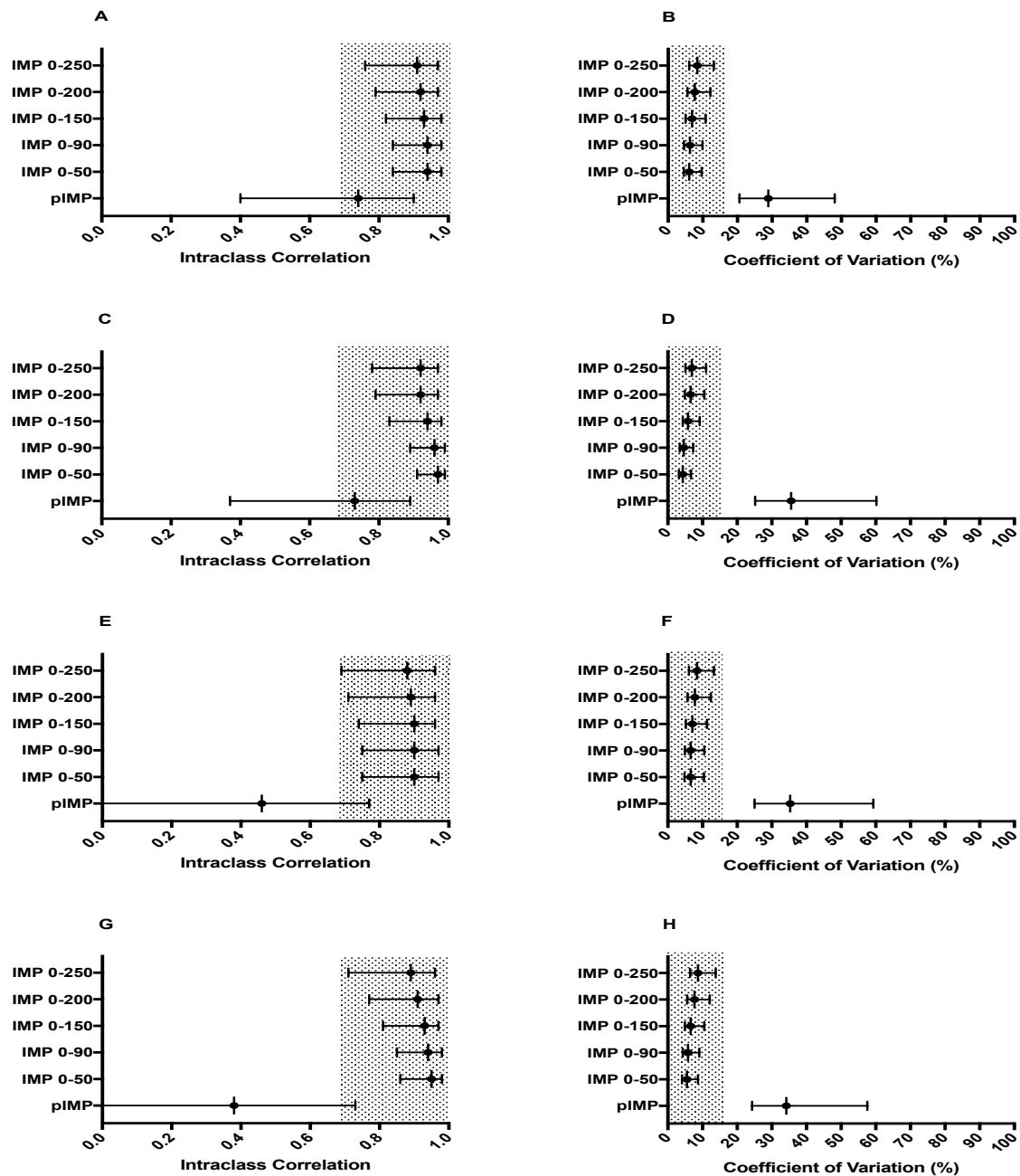


Figure 5.3 Between-Session Reliability Statistics for IMP Characteristics Generated in Each of the Four Testing Positions

Note: Grey shaded areas represented acceptable reliability ($ICC \geq 0.7$, $CV \leq 15\%$), error bars indicate 95% confidence limits. (A) ICC IMP characteristics in TRAD 1, (B) CV (%), (C) ICC IMP characteristics in TRAD 2, (D) CV (%), (E) ICC IMP characteristics in MT 1, (F) CV (%), (G) ICC IMP characteristics in MT 2, (H) CV (%). pIMP, peak impulse; IMP 0–50, IMP 0–50 ms sampling window; IMP 0–90, IMP 0–90 ms sampling window; IMP 0–150, IMP 0–150 ms sampling window; IMP 0–200, IMP 0–200 ms sampling window; IMP 0–250, IMP 0–250 ms sampling window.

TABLE 5.2 DESCRIPTIVE AND RELIABILITY STATISTICS FOR FORCE-TIME CHARACTERISTICS GENERATED IN TRAD 1 THAT DEMONSTRATE ACCEPTABLE RELIABILITY

Variable	Mean \pm SD T1	Mean \pm SD T2	ICC	95% CI		CV (%)	95% CI		TE	SWC _{0.2}	SWC _{0.5}
				Lower	Upper		Lower	Upper			
PF (N)	2748.38 \pm 730.00	2728.23 \pm 643.83	0.98	0.95	0.99	4.00	2.90	6.2	98.04	247.77	686.92
F ₅₀ (N)	1010.56 \pm 255.70	965.59 \pm 204.45	0.94	0.84	0.98	6.30	4.60	9.90	76.31	92.03	230.07
F ₉₀ (N)	1173.34 \pm 313.03	1094.63 \pm 246.31	0.93	0.81	0.97	7.50	5.50	11.80	100.02	111.87	279.67
F ₁₅₀ (N)	1456.34 \pm 403.36	1348.40 \pm 318.06	0.89	0.72	0.96	9.70	7.10	15.40	140.39	144.28	360.71
F ₂₀₀ (N)	1670.12 \pm 454.14	1537.89 \pm 360.31	0.86	0.64	0.95	11.10	8.10	17.80	179.20	162.89	407.23
F ₂₅₀ (N)	1877.53 \pm 510.16	1740.23 \pm 422.69	0.88	0.69	0.96	10.60	7.70	16.90	195.65	186.57	466.42
IMP ₀₋₅₀ (Ns)	47.85 \pm 11.94	46.36 \pm 9.64	0.94	0.84	0.98	6.10	4.50	9.70	3.54	4.32	10.79
IMP ₀₋₉₀ (Ns)	91.40 \pm 23.12	87.39 \pm 18.32	0.94	0.84	0.98	6.30	4.60	9.90	6.90	8.33	20.82
IMP ₀₋₁₅₀ (Ns)	170.58 \pm 44.29	160.83 \pm 35.20	0.93	0.82	0.98	6.90	5.00	10.80	13.43	15.90	39.75
IMP ₀₋₂₀₀ (Ns)	248.88 \pm 64.96	233.15 \pm 51.60	0.92	0.79	0.97	7.70	5.60	12.20	20.65	23.31	58.28
IMP ₀₋₂₅₀ (Ns)	337.71 \pm 87.96	315.10 \pm 70.18	0.91	0.76	0.97	8.40	6.10	13.20	29.27	31.63	79.07

TABLE 5.3 DESCRIPTIVE AND RELIABILITY STATISTICS FOR FORCE-TIME CHARACTERISTICS GENERATED IN TRAD 2 THAT DEMONSTRATE ACCEPTABLE RELIABILITY

Variable	Mean \pm SD T1	Mean \pm SD T2	ICC	95% CI		CV (%)	95% CI		TE	SWC _{0.2}	SWC _{0.5}
				Lower	Upper		Lower	Upper			
PF (N)	2117.79 \pm 522.43	2130.91 \pm 559.44	0.97	0.91	0.99	5.00	3.70	7.80	102.17	216.37	540.93
F ₅₀ (N)	851.52 \pm 176.54	872.76 \pm 182.69	0.96	0.89	0.99	4.70	3.40	7.30	36.95	71.85	179.61
F ₉₀ (N)	938.27 \pm 203.84	956.65 \pm 192.42	0.92	0.80	0.97	6.50	4.80	10.30	58.83	79.25	198.13
F ₁₅₀ (N)	1139.05 \pm 274.06	1138.90 \pm 228.50	0.88	0.69	0.96	8.70	6.30	13.80	98.52	100.51	251.28
F ₂₀₀ (N)	1297.21 \pm 319.28	1283.66 \pm 257.64	0.88	0.69	0.96	8.70	6.40	13.80	113.06	115.39	288.46
F ₂₅₀ (N)	1429.40 \pm 338.54	1415.68 \pm 284.45	0.91	0.76	0.97	7.40	5.40	11.60	103.78	124.60	311.50
IMP ₀₋₅₀ (Ns)	41.33 \pm 8.58	42.33 \pm 9.05	0.97	0.91	0.99	4.30	3.20	6.70	1.61	3.53	8.82
IMP ₀₋₉₀ (Ns)	77.01 \pm 16.25	78.80 \pm 16.44	0.96	0.89	0.99	4.60	3.40	7.30	3.30	6.50	16.25
IMP ₀₋₁₅₀ (Ns)	139.27 \pm 30.00	141.60 \pm 28.64	0.94	0.83	0.98	5.80	4.30	9.20	7.72	11.73	29.32
IMP ₀₋₂₀₀ (Ns)	200.37 \pm 44.61	202.31 \pm 40.47	0.92	0.79	0.97	6.60	4.90	10.50	12.93	17.02	42.54
IMP ₀₋₂₅₀ (Ns)	268.68 \pm 60.85	269.86 \pm 53.65	0.92	0.78	0.97	6.90	5.10	11.00	18.24	22.90	63.73

TABLE 5.4 DESCRIPTIVE AND RELIABILITY STATISTICS FOR FORCE-TIME CHARACTERISTICS GENERATED IN MT 1 THAT DEMONSTRATE ACCEPTABLE RELIABILITY

Variable	Mean \pm SD T1	Mean \pm SD T2	ICC	95% CI		CV (%)	95% CI		TE	SWC _{0.2}	SWC _{0.5}
				Lower	Upper		Lower	Upper			
PF (N)	2425.37 \pm 689.85	2435.65 \pm 498.13	0.84	0.59	0.94	11.10	8.10	17.70	268.01	237.59	593.99
F ₅₀ (N)	921.71 \pm 187.25	951.68 \pm 164.31	0.90	0.40	0.96	6.70	4.90	10.50	58.29	70.31	175.78
F ₉₀ (N)	1011.21 \pm 229.44	1043.72 \pm 187.89	0.90	0.74	0.96	7.20	5.20	11.30	69.33	83.47	208.67
F ₁₅₀ (N)	1208.21 \pm 336.67	1242.34 \pm 249.78	0.88	0.68	0.96	9.30	6.80	14.70	115.04	117.29	293.23
F ₂₀₀ (N)	1372.02 \pm 409.76	1405.81 \pm 286.19	0.86	0.65	0.95	10.40	7.60	16.50	151.13	139.19	347.98
F ₂₅₀ (N)	1521.98 \pm 452.39	1559.56 \pm 316.65	0.87	0.67	0.95	10.20	7.50	16.30	162.18	153.81	384.52
IMP ₀₋₅₀ (Ns)	44.76 \pm 8.87	45.97 \pm 7.96	0.90	0.75	0.97	6.60	4.80	10.40	2.81	3.37	8.42
IMP ₀₋₉₀ (Ns)	83.29 \pm 17.05	85.74 \pm 14.81	0.90	0.75	0.97	6.60	4.90	10.50	5.25	6.37	15.93
IMP ₀₋₁₅₀ (Ns)	149.81 \pm 33.64	154.26 \pm 27.30	0.90	0.74	0.94	7.10	5.20	11.30	10.30	12.19	30.47
IMP ₀₋₂₀₀ (Ns)	214.50 \pm 52.10	220.57 \pm 39.99	0.89	0.71	0.96	7.80	5.70	12.40	16.65	18.42	46.05

TABLE 5.5 DESCRIPTIVE AND RELIABILITY STATISTICS FOR FORCE-TIME CHARACTERISTICS IN MT 2 THAT DEMONSTRATE ACCEPTABLE RELIABILITY

Variable	Mean \pm SD T1	Mean \pm SD T2	ICC	95% CI		CV (%)	95% CI		TE	SWC _{0.2}	SWC _{0.5}
				Lower	Upper		Lower	Upper			
PF (N)	2746.23 \pm 717.06	2810.19 \pm 672.41	0.92	0.78	0.97	8.00	5.90	12.70	217.16	277.89	694.73
F ₅₀ (N)	1017.54 \pm 230.57	1038.56 \pm 218.08	0.94	0.85	0.98	5.80	4.20	9.10	58.43	89.73	224.33
F ₉₀ (N)	1102.11 \pm 266.12	1118.30 \pm 236.44	0.93	0.80	0.97	6.80	5.00	10.80	74.53	100.51	251.28
F ₁₅₀ (N)	1294.31 \pm 352.05	1311.89 \pm 286.61	0.88	0.70	0.96	9.50	6.90	15.00	119.24	127.73	319.33
F ₂₀₀ (N)	1470.60 \pm 426.38	1495.76 \pm 327.08	0.84	0.60	0.94	11.60	8.50	18.60	167.03	150.69	376.73
F ₂₅₀ (N)	1658.70 \pm 491.04	1683.30 \pm 361.61	0.80	0.52	0.92	13.30	9.70	21.40	213.20	170.53	426.32
IMP ₀₋₅₀ (Ns)	49.66 \pm 11.07	50.63 \pm 10.66	0.95	0.86	0.98	5.50	4.10	8.70	2.79	4.35	10.87
IMP ₀₋₉₀ (Ns)	91.94 \pm 20.88	93.65 \pm 19.68	0.94	0.85	0.98	5.80	4.30	9.10	5.36	8.11	20.28
IMP ₀₋₁₅₀ (Ns)	163.72 \pm 39.14	166.30 \pm 35.06	0.93	0.81	0.97	6.60	4.90	10.50	7.99	14.84	37.10
IMP ₀₋₂₀₀ (Ns)	232.89 \pm 58.25	236.52 \pm 50.05	0.91	0.77	0.97	7.70	5.60	12.10	17.69	21.66	54.15
IMP ₀₋₂₅₀ (Ns)	311.13 \pm 80.70	316.09 \pm 66.65	0.89	0.71	0.96	8.70	6.40	13.80	26.92	29.47	73.68

5.4 Discussion

The primary finding of this study was that, regardless of the body and barbell position utilised during performance of the IMTP, RFD, both peak and time-specific, are not reliable measures of skeletal muscle function. Furthermore, the data suggested that the use of specific time-bands for the determination of IMP was more reliable than utilising a peak value, while force output was entirely unaffected by alterations in barbell position and body posture. The results in this study provide further insight into the correct methodology of assessment for skeletal muscle function using the IMTP.

Previously, PF measured in the IMTP has been shown to be a highly reliable measure, with ICC and CV values of 0.96–0.99 and 1.7–4.3% respectively (20, 23, 56, 119, 121). This study reports similar ICC and CV values regardless of testing position used (See Tables 5.2–5.5). Haff et al. (56) reported that force at 30, 50, 90, 100, 150, 200 and 250 ms demonstrated very high ICC (0.99) and very low CV values (2.3–2.7%) when utilising a barbell and body position matching the second pull of the clean, while Beckham et al. (20) similarly reported that force at 50, 90, 200 and 250 ms are reliable in the same position. This study reports similar reliability results for time-specific force to both Haff et al. (56) and Beckham et al. (20), with time-specific force at all recorded epochs reliable in each testing position. Furthermore, TtPF demonstrated poor reliability across all testing positions examined in this study.

While the force outputs generated in this study are equally reliable in all testing positions, the current literature suggests that the magnitude of the force output generated is substantially affected by changes in position (19, 20, 37). Although Comfort et al. (31) reported no significant differences between the force-time characteristics generated in nine differing combinations of hip- and knee-angles or a self-selected body posture, provided the barbell was maintained at the mid-point between the iliac crest and patella, both Beckham et al. (19) and Beckham et al. (20) have reported that a position that matches the second pull of the clean produces significantly greater force outcomes than a lower barbell position with a concurrently inclined body posture. Similarly, Dos'Santos et al. (37) reported that utilising an upright torso angle of 145° results in significantly greater force and RFD variables than a reclined torso angle of 175°, while using a barbell position that matches the second pull of the clean. Therefore, based upon the results of this study and the available literature, altering the testing position used for the IMTP does not affect the reliability of peak and time-specific force variables generated, though

altering body posture away from the posture found during the second pull of the clean and adopting a lower barbell position may reduce the magnitude of those force variables generated and therefore present a less accurate assessment of the athlete's true physical capabilities. The consistent preferential use of a position that matches the second pull of the clean will aid in the improvement of the reliability of force-time characteristics generated and provide the ability for strength and conditioning professionals to accurately compare their athletes to other populations if they wish (29).

Similar to time-specific force, previous research has suggested that RFD in specific time-bands are reliable within-session in the IMTP, with Haff et al. (56) reporting within-session ICC and CV values of >0.7 and $<15\%$ for time-bands of 0–30 ms, 0–50 ms, 0–90 ms, 0–150 ms, 0–200 ms and 0–250 ms. Furthermore, Comfort et al. (31) reported that pRFD was reliable between sessions, regardless of the body posture adopted during trials. This study however found that regardless of the position used during performance of the IMTP, CV values for all RFD time-bands were above both the 10% limit of Brady et al. (23) and the 15% limit used by both this study and Haff et al. (56). Furthermore, pRFD calculated using a 20 ms sampling window was also deemed unreliable as while the ICC meet the required limit in all positions, the CV was $>15\%$ regardless of position. This conflicts with the results of Comfort et al. (31), who reported that pRFD calculated within a 1.67 ms sampling window was reliable between testing sessions regardless of the body posture used. Both Haff et al. (56) and Brady et al. (23) however have reported that both a 1 and 2 ms sampling window are unreliable within-session. As such, when the within-session reliability results of Haff et al. (56) and Brady et al. (23) are taken in conjunction with the between-session reliability results of the current study it does appear that pRFD, regardless of sampling window, body posture and barbell position used, should be used with caution when assessing skeletal muscle function. Strength and conditioning professionals should assess the reliability of force-time characteristics generated by their specific population to determine their suitability for use in assessing skeletal muscle function.

It is unclear why differences in the reliability of RFD characteristics have been found between the subject groups of Brady et al. (23), Comfort et al. (31) and Haff et al. (56) and this study. One potential explanation may be the differing levels of familiarisation present in the three studies (83). Beckham et al. (18) reported that a single familiarisation session of four submaximal IMTP efforts was adequate to optimise force production, however as

RFD was not examined it is unclear whether the same amount of familiarisation is sufficient to optimise RFD characteristics. While the IMTP appears to require less familiarisation to optimise force characteristics than other comparable isometric multi-joint tests like the isometric squat (18, 40), it is still unclear within the current body of scientific literature the volume of pre-testing familiarisation required to optimise the reliability of RFD characteristics. As such, further research in this area is required. Furthermore, in contrast to the participants in this study, the participants in Haff et al. (56) (collegiate volleyball players) regularly performed the IMTP as part of their athlete monitoring program. As a result, those participants may possess a considerably greater ability to rapidly produce force isometrically due to the learning effect (83) than the participants examined by Brady et al. (23) and in this study, who were generally performing the test for the first time during the familiarisation session. It is therefore a plausible suggestion that RFD characteristics generated in the IMTP require substantially greater amounts of familiarisation when compared to force characteristics to produce reliable results (83) and may also explain the disparity in the reliability reported between studies.

Unlike RFD time-bands, this study found that IMP time-bands are highly reliable between-sessions regardless of position ($ICC = 0.92\text{--}0.97$, $CV = 4\text{--}8.7\%$), which aligns with the results of Comfort et al. (31) who reported that IMP_{100} , IMP_{200} and IMP_{300} are reliable both within and between testing sessions. Brady et al. (23) however reported that IMP_{100} , IMP_{200} and IMP_{250} was unreliable within-session when using an IMTP testing position that matched the second pull of the clean, though IMP_{300} was deemed reliable. Furthermore, unlike the current study which found no significant differences between the IMP characteristics generated in each session, Thomas et al. (120) reported small significant differences between-sessions in the IMP generated at 100, 200 and 250 ms, therefore rendering these IMP characteristics unreliable. Similar to the unknown cause for the differences in the reliability of RFD characteristics reported by different subject populations despite the use of the same IMTP protocol, it is unclear why studies have reported different reliability statistics for time-specific IMP characteristics. A potential reason is, that like both force and RFD characteristics, it is possible the level of familiarisation with the IMTP possessed by the participants may affect the reliability of IMP characteristics. It is plausible that participants with greater experience performing the IMTP and/or dynamic weightlifting movements initiated from the second pull position generate more reliable force-time characteristics overall when compared to participants

with a lesser degree of experience in both the IMTP and dynamic weightlifting movements initiated from the second pull position.

Of particular note in this study was the exclusion of one participant due to excessive changes in body posture upon the initiation of trials. While Beckham et al. (20) demonstrated that a small amount of hip and knee extension is unavoidable during IMTP trials regardless of the use of pre-tension to reduce slack in the “system,” the participant in this study shifted from an inclined torso position (125°) to a near vertical upright torso position upon trial initiation, in a manner similar to the re-positioning that occurs during the transition from the first to second pull in the weightlifting movements. Beckham et al. (20) reported a similar occurrence, with one participant changing position in a similar fashion to the participant in this study. Furthermore, Beckham et al. (20) reported that a further two participants were unable to attain the required position as described by Comfort et al. (31). These changes in torso angle and the inability of some participants to attain the correct body posture, although rare, suggest that the initial starting position of the IMTP should be solely determined by the anthropometrics of the individual athlete, not a single standardized set of hip and knee angles that each individual in the testing cohort are forced to adopt.

There are some limitations that should be taken into consideration when examining the practicality of the results of this study. First, the participant population is somewhat homogenous in that they were all strength-power athletes with experience in the weightlifting movements. Athletes who are less experienced in the weightlifting movements, who compete in other sporting disciplines such as track and field, or compete in field-based sports (i.e., rugby, soccer and hockey) may display differing abilities in producing reliable force-time characteristics. Second, while the participants were visually monitored for changes in body posture upon force application, no direct video analysis of movement changes were monitored. It is therefore unknown the degree to which the participants who took part in this study altered their body position, which may adversely affect the reliability of force-time characteristics in isometric tests (83). Finally, while the visual identification of force-onset has been suggested by some as the optimal method in isometric trials (123, 124), recent research has suggested that the use of algorithm- or threshold-based automatic detection methods may be superior (27, 122). However, as yet, only limited research has examined this topic and further research should be performed

to assess the effect of automated force-onset detection methods on the reliability of force-time characteristics.

5.5 Conclusions

The results of this study suggest that regardless of testing position used during the IMTP, both PF and time-specific force are reliable tools for the assessment of athlete's skeletal muscle function. Conversely, the use of pRFD and RFD time-bands as monitoring or diagnostic tools should be done with caution as unreliable results may occur if the participants are not highly experienced with the testing protocol and dynamic weightlifting movements initiated from the mid-thigh position. Strength and conditioning professionals should therefore consider the preferential use of IMP time-bands in place of RFD characteristics, as IMP time-bands demonstrate a high degree of between-session reliability that is unaffected by deviations in testing position. Considering that IMP is strongly related to sprinting, jumping and change of direction ability, the use of IMP time-bands may provide superior diagnostic information to practitioners when compared to RFD variables. Further research examining these relationships across a wide range of sports should be undertaken however, as the evidence presently available within the literature specifically examining the relationships between IMP in the IMTP and markers of athletic performance is limited. The use of pIMP as an assessment and/or diagnostic tool however should be avoided as the results of this study suggested it is highly unreliable, regardless of the testing position used.

Chapter 6 - Conclusions & Future Directions for Research

The aim of this thesis was to examine the force-time curve characteristics generated by changing IMTP testing position. Specifically, this thesis was designed to determine if: 1) altering the position used during performance of the IMTP affected both the reliability and magnitude of the force-time curve characteristics generated; and 2) provide clarity regarding the optimal IMTP testing position to be used during assessment of an athlete's skeletal muscle function. Therefore, two experimental studies were undertaken to determine whether performing the IMTP using a testing position that does not match the second pull of the clean has an effect on the force-time characteristics generated.

Experimental study one investigated the effect of using alternate IMTP testing positions on the within-session reliability and magnitude of force, RFD, and IMP characteristics. The primary finding of this study was that changes in both the body posture and the barbell position used during the IMTP did not affect the within-session reliability of the force-time characteristics generated. The magnitude of those characteristics however was significantly impacted. Specifically, an IMTP testing position that corresponded to the second pull of the clean resulted in significantly greater PF, time-specific force, pRFD₂₀, and IMP time-bands than a testing position that utilised a bent-over torso angle, regardless of barbell position. Additionally, regardless of the testing position adopted, both RFD time-bands and pIMP were unreliable within-session. While the findings of this study did not support the hypothesis that changes in testing position away from one corresponding to the second pull of the clean would result in unreliable force-time characteristics, they did support the hypothesis that changes in testing position would detrimentally affect their magnitude.

Experimental study two investigated the effects of using an IMTP testing position that did not correspond to the second pull of the clean on the between-session reliability of force, RFD, and IMP characteristics generated. The primary finding of study two was the use of body postures and barbell positions that did not correspond to the second pull of the clean did not adversely affect the between-session reliability of any force-time characteristic. Furthermore, regardless of the testing position used, TtPF, RFD time-bands, and pIMP were unreliable. While previous research has examined the between-session reliability of force characteristics and pRFD in the IMTP (36), the between-session reliability of time-specific RFD characteristics has not been previously reported. Importantly, while some evidence within the literature and the results of study one in

this thesis suggests that pRFD_{20} may be reliable within-session, study two reported that it was unreliable between-sessions. As such, its future use as an assessment tool should be done with caution or avoided in favour of reliable characteristics such as PF, time-specific force, and IMP time-bands.

Therefore, when taken collectively, the results reported in both study one and study two suggest that when performing the IMTP a position that corresponds to the second pull of the clean should be preferentially used. This position allows for the optimisation of the force-time characteristics generated during the tests and as such the most accurate assessment of skeletal muscle function. Furthermore, when using the IMTP to assess skeletal muscle function, strength and conditioning professionals and sports scientists should primarily use PF, time-specific force, and IMP time-bands as these characteristics are reliable both within- and between-sessions. The use of pRFD_{20} as an assessment tool to monitor adaptations to training interventions should be done with caution due to the likelihood of measurement error obscuring results across time. This may particularly be the case in those athletes who possess limited experience with both the IMTP and dynamic weightlifting movements initiated from the second pull position. Moreover, while the results reported within this thesis suggest that force and IMP characteristics are sufficiently reliable for use as assessment tools, practitioners should none the less establish the reliability of these measures for their own athlete cohort to ensure that accurate results are used to monitor and guide future training.

While the results and subsequent conclusions from this thesis demonstrate interesting and practically applicable findings that have the potential to influence the practices of strength and conditioning professionals and sports scientists, there remain several gaps within the literature examining the IMTP. The reliability results in both study one and study two suggest that both pRFD and RFD time-bands are unreliable in athletes with limited experience performing the IMTP and/or dynamic weightlifting movements initiated from the second pull position. It has however been suggested that those athletes with considerable experience may be better able to produce reliable RFD characteristics (56) and as such the generation of reliable RFD characteristics in the IMTP may require substantial familiarity with the test. Unlike the level of familiarisation required to optimise force characteristics (18), the level of familiarisation required to generate reliable RFD characteristics is unknown. Considering the limited time typically available to be allotted to testing in athletic environments, the number of sessions required to make

RFD characteristics a viable measurement tool for longitudinal tracking of skeletal muscle function is of considerable interest.

Furthermore, it is currently uncertain what effect, if any, the visual identification of force onset has upon force-time characteristics when compared to automated identification methods. It is plausible that the differences in force-time curve data analysis methodologies used potentially lead to the variability in the reliability and magnitude of the force-time characteristics reported within the current body of literature. While algorithmic methods have been reported as reliable in the IMTP, they as yet have only been compared in a limited fashion to visual identification (27). Furthermore, while an automated identification threshold of 5 SDs of an athlete's pre-trial body weight has been shown to be more accurate than percentages of the athlete's bodyweight (34), this too has not been compared to visual identification. Considering automated methods have displayed higher and more variable error rates than visual identification in other isometric testing modalities (124), it is plausible these same error rates exist in the IMTP and therefore may substantially affect the analysis of the force-time curve data collected. As such the most reliable and accurate method of identifying the onset of force application during an IMTP trial should be determined, allowing for consistent and accurate assessment of an athlete's force generating capacity. Finally, while there has been some research examining sex differences in the IMTP, it has only been one study and as such only the results of a small sample are known. Future research should look again at the sex differences between men and women when performing both the IMTP and the ISqT with the aim of studying both field-based and individual sports.

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Appendices

The Appendices are not included in this version of the thesis.